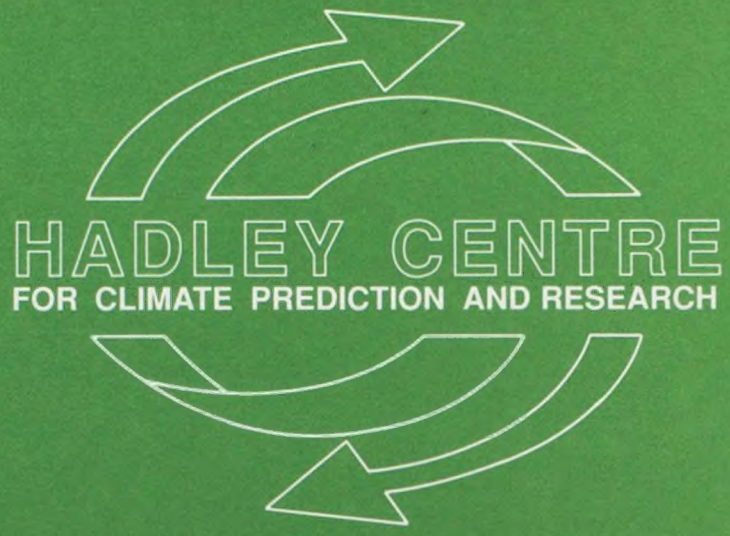

The greenhouse effect and its likely consequences for climate change.

by

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CLIMATE
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THE GREENHOUSE EFFECT AND ITS LIKELY CONSEQUENCES FOR CLIMATE CHANGE

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THE GREENHOUSE EFFECT AND ITS LIKELY IMPLICATIONS FOR CLIMATE CHANGE

D J CARSON

(Paper presented at the University College of Wales, Aberystwyth, Agricultural Society Conference 1990, 9 November 1990)

1. Introduction

There is widespread concern that continual man-made emissions of so-called 'greenhouse gases' are resulting in global atmospheric warming, local climate changes and sea-level rise, with the prospect of consequent serious environmental, social and economic impacts. This paper focuses on some of the issues involved in understanding and modelling the climate system and, in particular, the uncertainties that must be reduced in order to predict climate change with confidence.

The most comprehensive scientific assessment of climate change was conducted by Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC), which is sponsored jointly by the World Meteorological Organisation and the United Nations Environment Programme. The result (Houghton et al, 1990) is the most authoritative and strongly supported statement on climate change that has ever been made by the international scientific community. Many of the points discussed briefly in this paper are addressed more fully in the IPCC Report.

2. The Greenhouse Effect

Consider the situation of solar radiation being received at the Earth's surface in the absence of an atmosphere. Some of the incoming solar radiation would be reflected at the surface and some fraction would be absorbed. In turn the Earth would emit radiation at a longer wavelength, due to it having a lower temperature than that of the Sun, and this would escape to space. For an equilibrium temperature to be maintained, the net incoming shortwave radiation at the surface has to be balanced by the outgoing long-wave radiation. At equilibrium the effective radiating temperature of the Earth is about 255K (-18 °C). In the absence of an atmosphere, this would be the Earth's surface temperature.

However, the Earth has an atmosphere, with certain gases, principally water vapour and carbon dioxide, whose properties for the shorter solar wavelengths are quite different to those at the longer infrared (or terrestrial) wavelengths. What happens is that some of the long-wave radiation from the surface is absorbed by these gases within the lower atmosphere (the troposphere) and then it is re-emitted, both downwards, warming the surface and lower atmosphere, and upwards. To maintain overall equilibrium there must be radiative balance at the top of the atmosphere and corresponding energy balances at the surface and within the atmosphere.

In this way such gases effectively trap long-wave radiation that would otherwise escape from the Earth. They are termed greenhouse gases and this radiative mechanism which influences the temperature of the surface and the atmosphere is called the **Greenhouse Effect**. The effect of the greenhouse gases is to raise the surface temperature by about 33K to 288K (15 °C). The natural greenhouse effect is therefore vital to sustain life on Earth as we know it.

3. How Do We Know that the Natural Greenhouse Effect Is Real ?

a. In recent times, the mean temperature of the Earth's surface is warmer by about 33 K than it would be if the natural greenhouse gases were not present. Satellite observations of the radiation emitted from the Earth's surface and through the atmosphere can now demonstrate the effect of the greenhouse gases.

b. We know that the composition of the atmospheres of Venus, Earth and Mars are very different, and their surface temperatures are in general agreement with greenhouse theory. Mars, with its relatively thin atmosphere, is believed to have a very weak greenhouse warming effect (about 10K). Venus, which has a dense carbon dioxide atmosphere has a very large greenhouse effect, with a warming of about 523K.

c. Measurements from ice cores going back 160,000 years show very striking evidence of strong positive correlations between temperature and carbon dioxide (and methane) changes in the atmosphere (Fig 1). Although we do not know the details of cause and effect, calculations indicate that changes in these greenhouse gases were part, but not all, of the reason for the large (5-7K) global temperature swings between ice ages and interglacial periods.

4. Why the Cause for Concern ?

What now gives acute cause for concern is the evidence of significant, recent increases in concentrations of several of the radiatively active gases. In particular, the atmospheric concentrations of the main man-made greenhouse gases, namely, carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs), have all been increasing since the industrial revolution, and more rapidly so over the last few decades (Fig 2). The rise in carbon dioxide is attributed mainly to the burning of fossil fuels (coal, oil, gas). Deforestation is also believed to be a contributory factor which was more significant in earlier years.

One gas which is often neglected is tropospheric ozone, mainly because trends (particularly near the tropopause where it is most effective as a greenhouse gas) are not well established. Nonetheless, there are strong indications that tropospheric ozone has doubled over the last century, at least in the Northern Hemisphere.

If the theory of the greenhouse effect is correct, this should result in an enhanced greenhouse effect, which would disturb the current radiative balance and could, it is predicted, bring about significant climate change by the middle of the next century.

Examination of the lifetimes of the greenhouse gases shows that some of them (eg carbon dioxide, CFCs and nitrous oxide) are a hundred years or more. This means that their atmospheric concentrations will respond only slowly to changes in emissions and, in order to stabilise concentrations, very large reductions would have to be made in emissions - about 70% in the case of carbon dioxide.

Each greenhouse gas has a different effectiveness in modifying climate, due to its lifetime and the strength and position of its absorption in the infrared spectrum. We can find their relative strengths by considering the effect over 100 years of unit mass emission of each gas; this defines the Global Warming Potential index. It is found that, if carbon dioxide is given a value of unity, methane is about 20 times more effective, nitrous oxide about 300 times and the CFCs several thousand times more effective than CO_2. Although many CFC replacements are not damaging to the ozone layer, we should be aware that some of them can be effective greenhouse gases, although generally less so than the fully halogenated CFCs. Although CO_2 is the least effective per kg, because it is released in such vast quantities, it makes by far the biggest contribution (greater than 50%) to total climate forcing and will continue to do so over the next 100 years.

5. Is there Any Evidence of an Enhanced Greenhouse Effect ?

Analyses of observational records show that the global mean temperature has warmed by about 0.5K since 1900. In particular, the 6 warmest years have occurred in the 1980s - 1990 being the warmest on record, to date.

However, although there is growing confidence in the overall warming since the beginning of the century, it is not possible to attribute this, fully or in part, to an enhanced greenhouse effect. In particular:

a. There is less agreement amongst climatologists for the period prior to 1900, during which some analyses suggest temperatures may have reached values up to 0.3K warmer than in the early part of this century. So the nature and magnitude of the change since 1860 are still subject to debate.

b. There is not a continuous upward trend (Fig 3). There is considerable interannual and inter-decadal variability during the period that cannot be ascribed to greenhouse gases alone. Although the fossil fuel releases of CO_2 rose steeply after the Second World War, from 1940 until the mid 1970s the global mean temperature changed very little. The globe did not warm and the

Northern Hemisphere actually cooled - yet over that period the greenhouse gas concentrations were increasing monotonically.

Although the Earth has warmed, it has not done so in exactly the way we would expect it to do as a result of the greenhouse effect alone. Indeed, there are long-term changes that are contrary to expectations from the greenhouse effect.

Analysis of climate variability is very complex. Any temperature increase to date resulting from an enhanced greenhouse effect is still small enough to be masked by natural climate variations. Any observed warming is not yet large enough to establish beyond doubt that it is due to an enhanced greenhouse effect. Climatologists estimate that it may be a decade or more before we can detect an unequivocal signal of greenhouse warming in the surface temperature record.

6. Should Climate Change Resulting from an Enhanced Greenhouse Effect Be Considered a Serious Threat ?

In spite of the lack of unequivocal evidence, many scientists believe that the observed warming this century is, at least in part, a direct consequence of an enhanced greenhouse effect.

The current inability to attribute a climatic response to the measured increase in greenhouse gases is not a crucial issue (yet), for the following reasons :

a. The physical basis of the greenhouse effect and its overall effect on our climate are well understood. The growth rate in CO_2 and the other trace gases has been so dramatic since pre-industrial times that it is inconceivable, physically, that this is not affecting the radiative balance of the atmosphere.

b. There is also the supportive evidence of our understanding from other planets and from the ice-core analyses already discussed.

c. Although it cannot be shown that the overall warming this century is the result of increasing greenhouse gases, its overall direction and magnitude lie within the estimated range of their effects. **The available evidence is not inconsistent with our understanding of the consequences of an enhanced greenhouse effect.**

d. Data other than temperature records are also being analysed, for example, glacier retreat, sea-levels, sea-ice thickness, and anomalous weather events. As in the case of the temperature records, none of these has yet provided positive, unequivocal detection of an enhanced greenhouse effect. However, evidence of worldwide glacier retreat in recent decades provides strong support for the estimated global-warming trend.

The search continues for a 'fingerprint' of greenhouse-gas induced climate change. This involves not only the detection of climate change but also the attribution of at least part of that change to the enhanced greenhouse effect.

In summary :

- the greenhouse effect is real
- Man's activities are increasing greenhouse gas concentrations
- over half climate forcing is due to carbon dioxide
- many greenhouse gases have lifetimes of 100+ years
- stabilisation of carbon dioxide emissions would still leave concentrations rising
- available evidence to date (from all sources) is, on balance, not inconsistent with our understanding of an enhanced greenhouse effect and the transient response (0.5-1 K) that many argue should have taken place by now.

The important point is that our understanding of the climate system and its sensitivity to greenhouse gases would have to be sadly adrift for us to dismiss the possibility of climate change.

7. Prediction of Climate Change

Much of the concern about climate change in response to increased atmospheric greenhouse gas concentrations stems not directly from observational data but from the results of mathematical models. Changes in global and regional climates due to greenhouse gases are likely to be small, slow and difficult to detect above natural fluctuations during the next decade or two, so it will be necessary to continue to rely heavily on the use of such models.

However, there are many uncertainties in our understanding of the climate system. These make prediction of the nature, magnitude and timing of climate change, particularly at regional (i.e. continental) and smaller scales, unreliable at present. The primary research objectives then, of centres such as the Hadley Centre, are to identify, quantify and consequently reduce these scientific uncertainties and thereby improve our ability to model the climate system and predict climate change. To do so, it is necessary to gain a better understanding of the processes and properties which govern climate (and, therefore, climate change) - through a combination of observational, theoretical and modelling studies.

8. The Climate System

The Climate System comprises not only the atmosphere but also the oceans, the cryosphere (ice and snow), the geosphere (in particular the land surface) and the biosphere. Each component has its characteristic response times to changes in current conditions. Fig 4 reminds us not only of the various components of the climate system but also of the variety and complexity of their mutual interactions. The system is regulated by complex and interactive dynamical, physical, chemical and biological processes. Small-scale interfacial processes play an important role in determining the current state and evolution of the system.

Two specific examples of its complexity and interactive nature are :

a. **Radiative transfer** within the atmosphere and energy exchange between the atmosphere and the underlying surface are complicated processes - as illustrated schematically in Fig 5. In equilibrium there must be net zero heating in each part of the system.

b. **The Hydrological Cycle**
A particular example of the need to consider interactions between different components of the system is that of the hydrological cycle. This represents the flow and storage of water in all its forms through the system. This is a particularly good example of storage or reservoir terms which can be very small but where fluxes between different parts of the system can be large and important.

This emphasises the need for process studies and also the interdisciplinary nature of the overall problem of climate modelling and climate-change prediction. In moving towards a holistic approach to tackling the problem of climate change, inputs are needed separately and collaboratively from meteorologists, oceanographers, glaciologists, hydrologists, biologists, geologists, etc.

9. The Central Role of Climate Modelling

The key to predictability is the development of a predictive numerical model of the climate system.

There are many different modelling approaches to studying the sensitivity of the climate system ranging from simple, 1-dimensional radiative-convective models and globally-averaged energy balance models to the full complexity of 3-dimensional atmospheric general circulation models (AGCMs) and coupled atmosphere-ocean general circulation models (AOGCMs). A point to stress is that although some models are much more complex, sophisticated, realistic and versatile than others - **ALL** are relatively simple when compared with the full complexity of the climate system itself.

In order to tackle the problem of predicting regional, transient climate change, the mathematical models used must allow in some way for the influences of the various components of the system and for the significant interactions between them. The type of model which holds out some promise for dealing with such complexity, most realistically, is that developed from existing 3-dimensional, global AOGCMs. These will provide an increasingly effective framework for testing new hypotheses for climate sensitivity and change.

Within the Meteorological Office particular emphasis is placed on developing a capability for 3-dimensional numerical modelling of the global climate using a coupled AOGCM and this modelling philosophy and commitment are at the heart of the Hadley Centre's programme. We are currently in the process of developing a new version of our coupled AOGCM which will run on our new CRAY computer, to be installed in March 1991 and which will be dedicated to climate-prediction research. The horizontal resolution of the atmospheric component of that model is 2.5° by 3.75° on a regular latitude-longitude grid and it will be used typically with 20 levels for the vertical resolution. This is the new Unified Model for both operational weather forecasting and climate research and prediction, so-called because the basic programming structures of the Meteorological Office's operational forecasting and climate models will, for the first time, be the same. This will increase the cost-effectiveness of their running and maintenance and also increase the highly-valued synergetic interaction between researchers engaged on developing and using the Unified Model in its climate mode and those engaged in similar activities with the operational-forecasting mode of the model.

10. Climate Feedbacks

Much of our understanding of how the various parts of the climate system work and interact with each other comes from climate modelling studies. However, a lack of basic knowledge of the processes involved, together with a lack of global data and limitations in computing power, mean that the predictive capability of current climate models is poor, particularly at the regional scale. There are no existing models (or any other techniques) which enable us to predict with any confidence how the climate is changing or will change over the UK in the next few decades. Indeed, current models give equilibrium globally-averaged surface temperature responses to a doubling of CO_2 which vary by a factor 3 or more.

In order to understand the motivation behind some of the current research programme of the Hadley Centre, let us consider why there should be such uncertainty and then look briefly at two examples of model sensitivity.

In spite of the complexity of radiative transfer through the climate system (Fig 5), given a change in concentration of greenhouse gases, it is relatively straightforward to calculate the implied change in radiative heating of the troposphere and the surface. However,

major uncertainties occur in trying to convert that change in heating into a temperature response of the atmosphere and the surface. The problem facing the modeller is to identify the significant so-called **feedback mechanisms** and to determine the sign and size of their various effects.

11. Two Examples of Uncertainties, Deficiencies and Sensitivities of Climate Models

a. Cloud-climate feedbacks

Recent modelling studies at the Meteorological Office (and elsewhere) have highlighted that the response of models to changing the concentrations of the greenhouse gases is very sensitive to the treatment of clouds (see Mitchell et al (1989)).

Typical AGCM sensitivity studies were carried out with 2 different cloud schemes :

i. a standard, simple cloud prediction scheme based on relative humidity

ii. a more complicated prescription including an explicit cloud water variable.

The result was that the average equilibrium surface warming in response to an effective doubling of CO_2 was reduced from 5.2K to 2.7K. In an additional experiment when cloud radiative properties were allowed to depend on the liquid water content of the clouds, the surface temperature response dropped still further to only 1.9K.

The spread 1.9K to 5.2K represents a factor of 2.7 in the response to changing the representation of clouds in the model. This result is compatible with a recent study (by Cess et al (1989)) in which 14 AGCMs were compared and found to have a 3-fold variation in global climate sensitivity caused largely by different cloud feedbacks. The uncertainty in how to formulate clouds poses a formidable obstacle to reliable climate prediction even in the equilibrium global mean sense, let alone in the context of transient, regional predictions.

b. Deforestation sensitivity studies

The AGCM lends itself as a natural testbed for sensitivity studies such as **'Amazon basin deforestation studies'**. By changing selected physical parameters in the land surface prescription over a chosen area, such a change can be simulated and its impact on the climate of the region (and of that further afield) can be tested.

Current models do demonstrate significant sensitivity to such changes in their formulation. One such experiment, carried out with a Hadley Centre model (Lean and Warrilow, 1989), shows a distinct

signal in the rainfall and temperature changes over the region as a result of a prescribed 'deforestation' (Figs 6 and 7).

Such studies are important, not only as an indicator of the sensitivities of the climate system and the possible consequences of the destruction of the Amazonian rainforest, but also as a means of gaining further insight into the way the whole interactive system reacts to accommodate such perturbations.

12. Quantifying the Feedback Processes

The above are but two examples of the uncertainties, deficiencies and sensitivities in the current generation of climate models which limit their predictive capability and demonstrate the need for more observations and basic research to quantify the feedback processes and reduce the uncertainties.

Such modelling studies suggest the following effects of internal feedbacks on the equilibrium warming in response to a doubling of CO_2 :

Process	Warming (K)
No feedback (other than re-establishment of new equilibrium as a result of black-body cooling)	1.2
+ Water vapour	1.7
+ Snow and ice	2.2
+ Cloud	1.9 - 5.2

13. Key Research Areas

A key aim is to identify, understand and quantify the feedbacks in the system so as to reduce the scientific uncertainties in the models. Many areas of sensitivity and uncertainty in climate modelling are already known, and with properly targeted research, there is every reason to hope that reliable predictions of many features of regional, transient climate change are attainable within a decade - or two.

In particular, more information is needed about

a. the influence of clouds

b. the circulation of the oceans and their interaction with the atmosphere

c. the interaction of the atmosphere with the land, the biosphere (on the land and in the oceans) and the cryosphere

d. the chemical cycles within the atmosphere and the biogeochemical cycles in the oceans.

14. Simulation of Present Climate

State-of-the-art AGCMs demonstrate considerable skill in reproducing the large-scale features of the current climate and such validation is a necessary step to be gone through with any model to be used for climate change experiments. The simplest way of validating a climate model is to prescribe present-day 'boundary conditions' and compare the long-term statistics of the resulting simulation with observed climatologies. This shows that AGCMs have considerable skill in the portrayal of the large-scale distribution of pressure, temperature, wind and precipitation in both summer and winter, although this success is due in part to the constraints on sea surface temperature and sea-ice. The current Hadley Centre models have been validated in this way and rank among the best available. There has been a general reduction in the errors in more recent AGCMs as a result of increased horizontal resolution, improvements to the parametrization of convection, cloudiness and surface processes and the introduction of parametrizations of gravity-wave drag.

15. Simulation of Climate Change

The models are also used to simulate the climate response to increased greenhouse gas concentrations. For example, Figs 8 (a) and (b) illustrate results from a Hadley Centre high-resolution model, showing typical equilibrium surface temperature responses due to doubling CO_2, averaged for December-February (DJF) and June-August (JJA), respectively.

Note the now well-documented results that :

- simulated changes in temperature vary considerably with longitude and season

- the largest warmings are over sea-ice in winter and smallest over sea-ice in summer. (This results from a good example of a positive feedback mechanism (the ice-albedo feedback) which involves snow-line retreat on land and sea-ice retreat.)

- responses are generally small in the tropics

- there is considerable geographical variation in warming within individual continents.

Although the large-scale features of the simulated temperature changes are consistent amongst the recognised main models, at this juncture the regional details vary considerably.

Again by way of example, Figs 9 and 10 show the corresponding results from a Hadley Centre model of precipitation changes and soil moisture changes, respectively.

The spatial patterns of climate change consequent on a doubling of CO_2 in the atmosphere vary from model to model, but there are a number of consistent changes which can also be understood in physical terms. The main conclusions from equilibrium-response studies conducted with climate models are :

- the lower atmosphere warms; stratosphere cools
- the global mean surface temperature change is 1.5 - 4.5 K; best estimate about 2.5K
- the warming is greatest in high latitude winter; least in the tropics
- global average precipitation increases (3-15%)
- soil moisture increases in winter high latitudes.

There are also some weaker indications that soil moisture decreases in summer NH midlatitudes and of an increase in tropical disturbances. Changes in climate variability are still unclear.

To investigate the climate consequences of emissions scenarios generated by the IPCC Working Groups, which would not justify the use of a large coupled AOGCM, simpler box-diffusion-upwelling models were used, which simulate the delaying effect of the oceans. The main scenario is the so-called Business-as-Usual (BaU) scenario, where it is assumed that no steps are taken to limit emissions. The climate forcing produced by this emission scenario gives an equivalent doubling of CO_2 by about 2025.

Fig 11 shows the estimated temperature change according to three levels of climate sensitivity (High, Medium, Low) which correspond to global equilibrium surface temperature responses to a doubling of CO_2 of 4.5K, 2.5K and 1.5K, respectively. For medium sensitivity and the BaU scenario, temperature rise is predicted to be about 0.3K per decade.

Taking global temperatures and comparing them with what the models predict for the last 100 years, we see that, if man-made greenhouse gases were the only factor operating, observations suggest a climate sensitivity of about 1.5K (i.e. low sensitivity). However, there are several other factors which can affect the temperature. As was noted earlier, natural variability could have accounted for almost all the temperature rise. Equally, natural variability could have offset a larger man-made temperature rise. When taken on a 50-year

period, it is likely that other climate forcings (eg solar, volcanic, man-made sulphur modification of cloud properties) will all be substantially less than that predicted from man-made greenhouse gases.

16. Climate Predictions

Based on medium sensitivity and the IPCC BaU scenario, the best current statements on climate-change are, in summary :

- temperatures will be 2K higher than pre-industrial values by 2030
- the rate of temperature rise will be about 0.3K per decade
- sea level will be about 20cm higher by 2030
- there are large uncertainties in any such predictions
- there has been a global warming of about 0.5K in last 100 years; this is compatible with, but not proof of, a man-made greenhouse effect.

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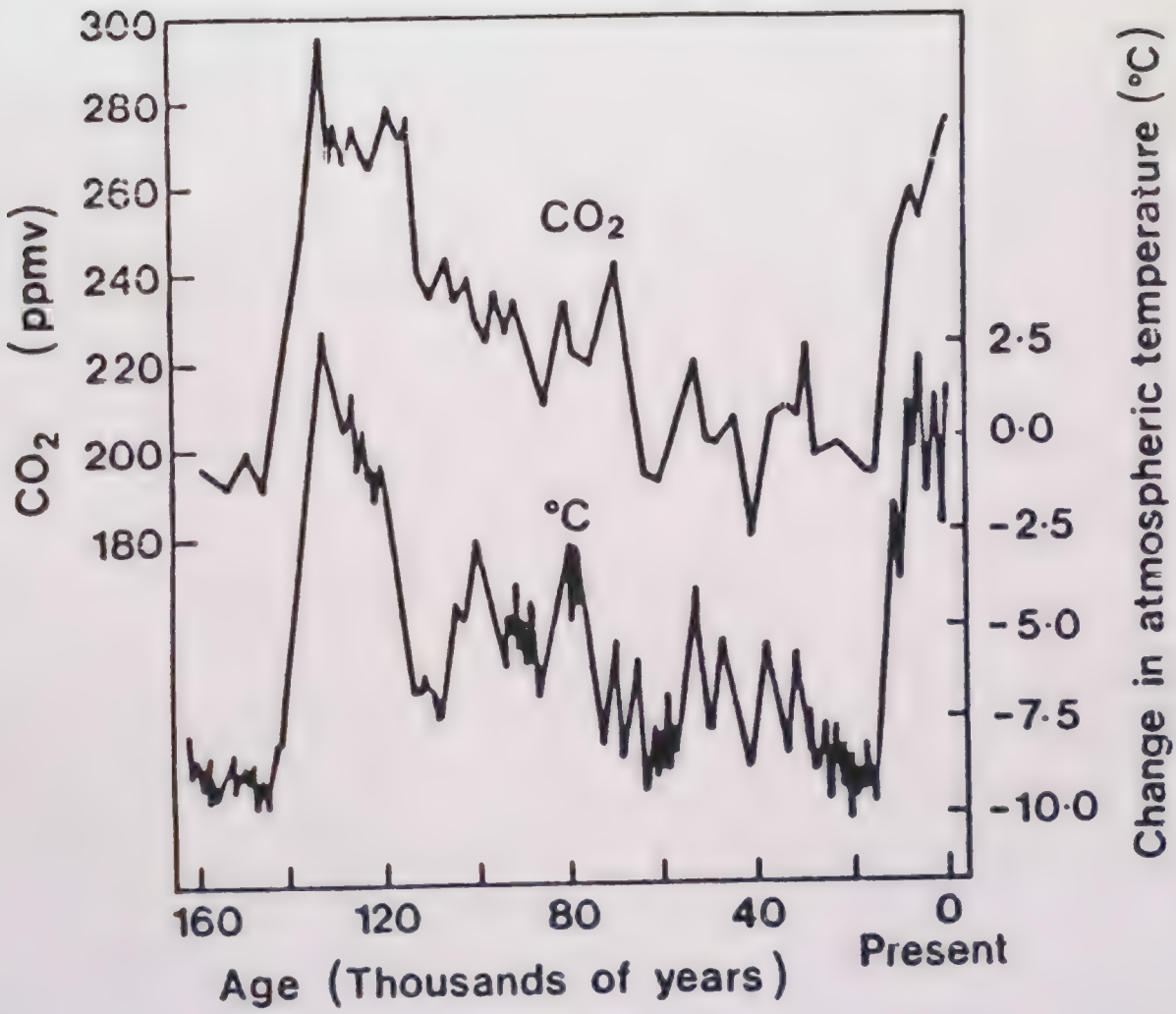


Fig 1. Analysis of air trapped in Antarctic ice cores shows that carbon dioxide concentrations were closely correlated with the local temperature over the last 160,000 years. (From Barnola et al (1987))

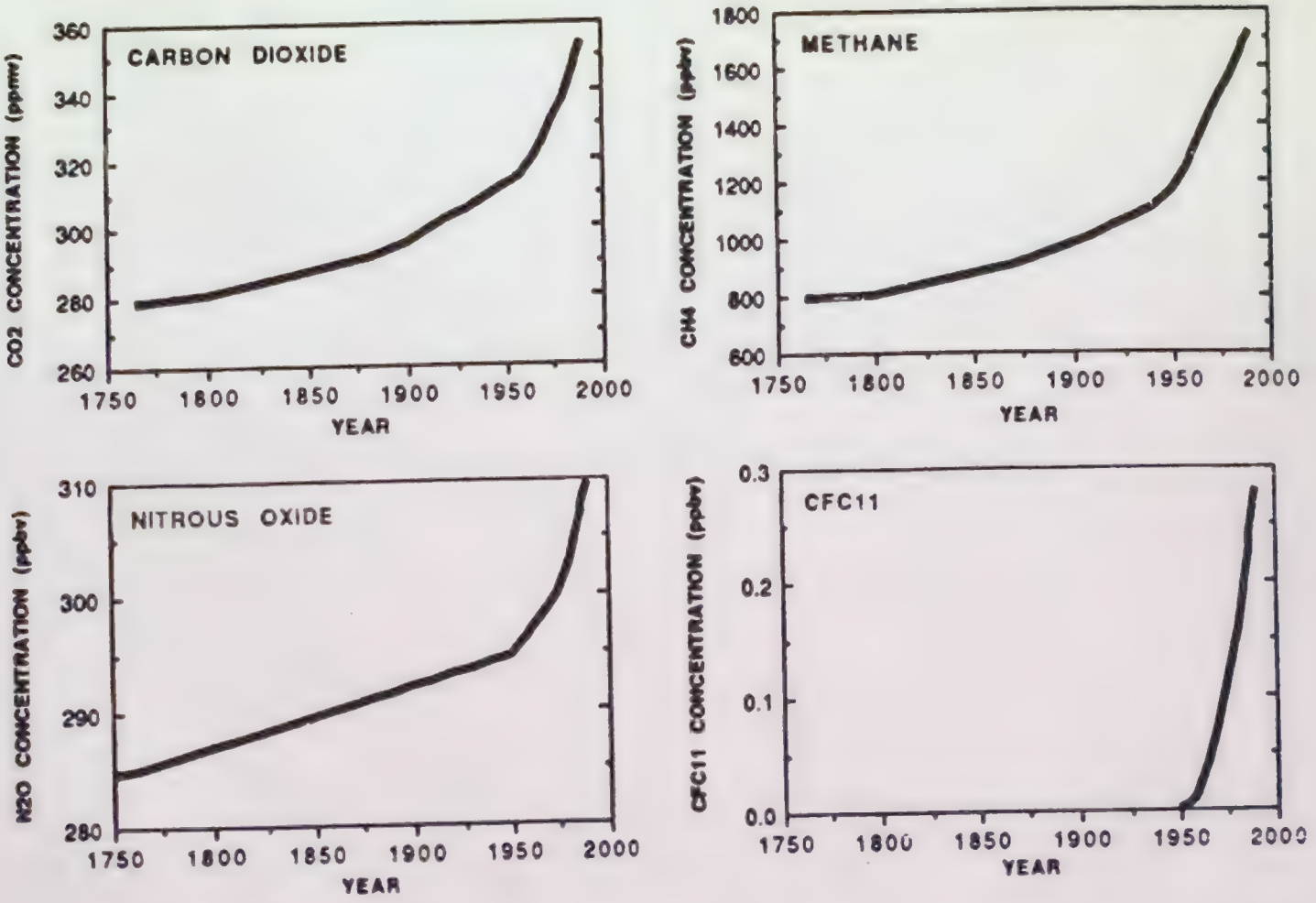


Fig 2. Greenhouse gas concentrations are rising due to man-made emissions. CFCs were not present in the atmosphere before the 1930s. (From Houghton et al (1990))

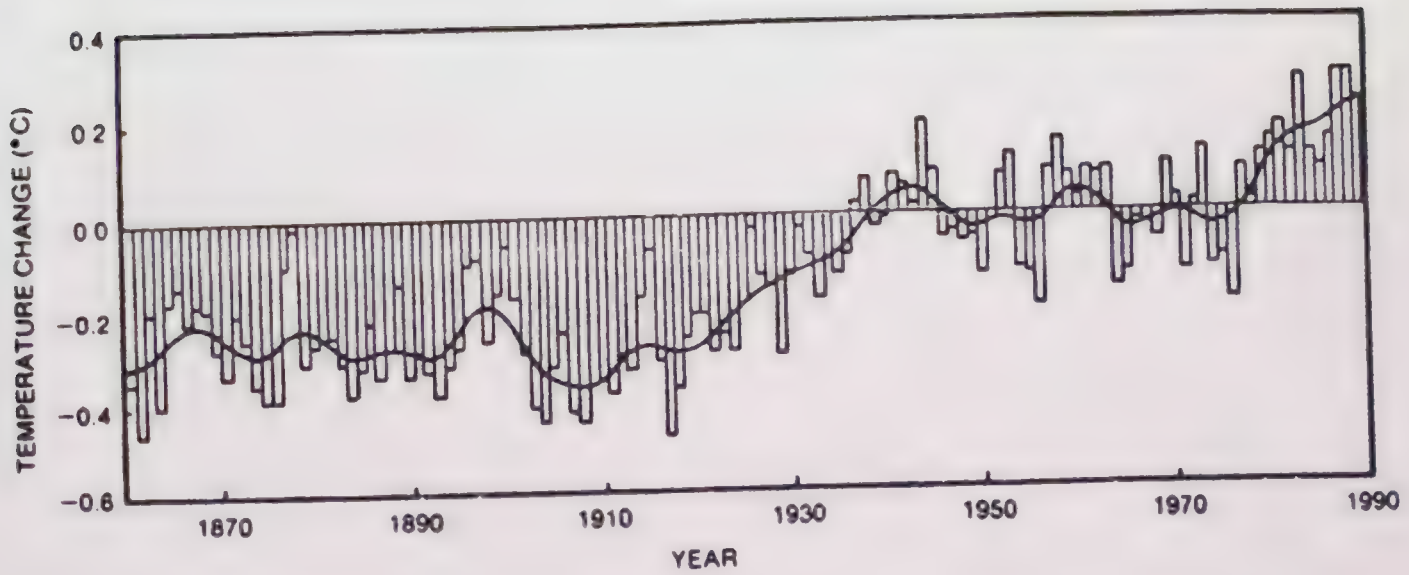


Fig 3. Annual deviation of global-mean combined land-air and sea-surface temperatures for the period 1861-1989 (shown by bars), relative to the average for 1951-80. The curve shows the results of a smoothing filter applied to the annual values. (From Houghton et al (1990))

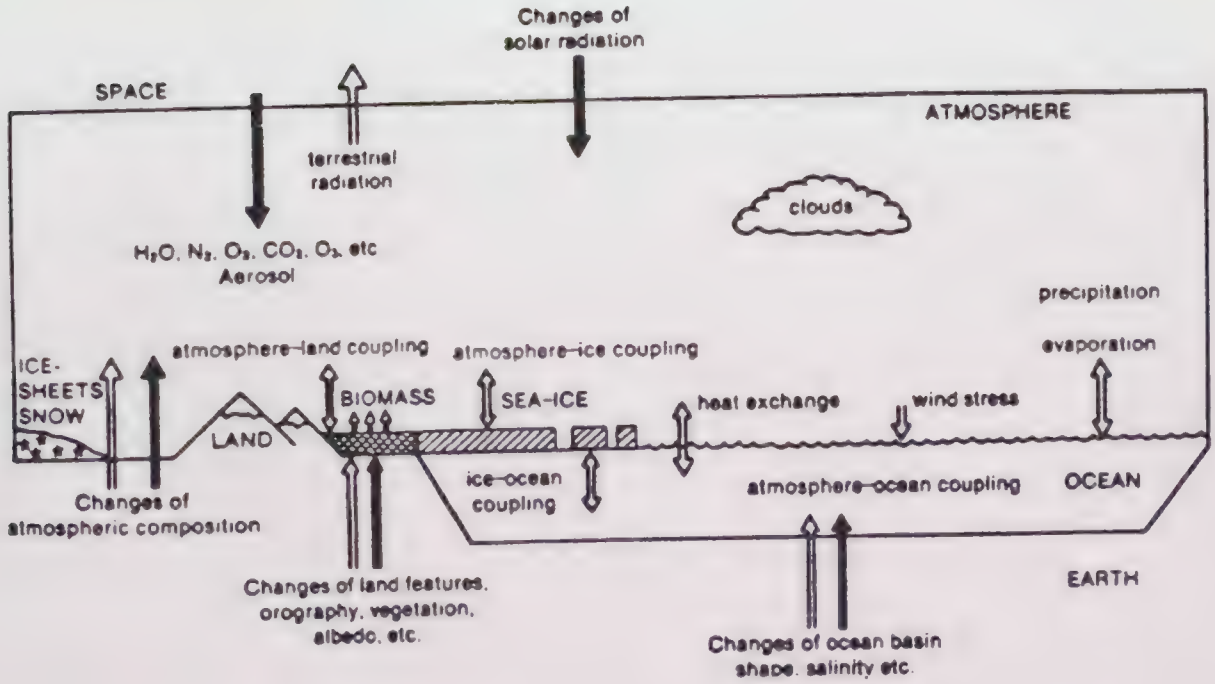


Fig 4. Schematic illustration of the climate system components and interactions. (From Houghton et al (1990))

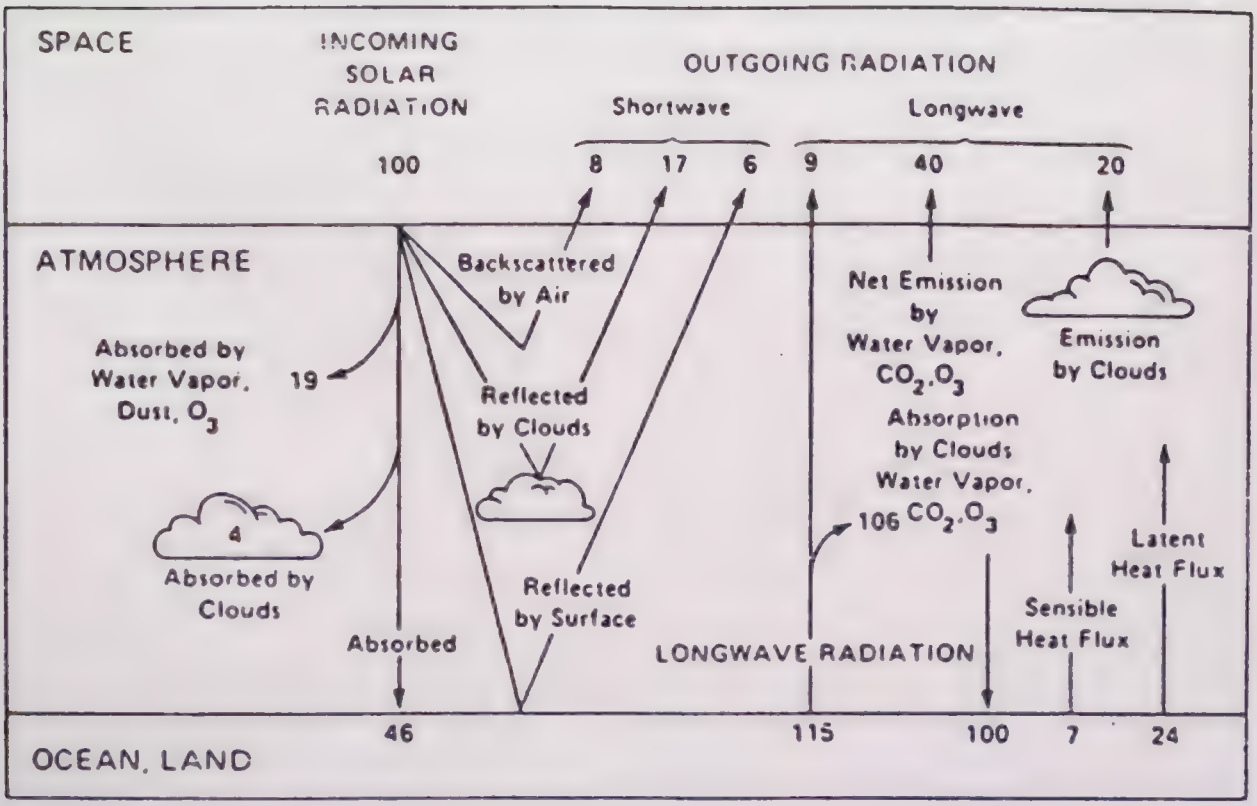


Fig 5. Schematic illustration of the atmospheric and surface heat balances. In the arbitrary units used, 100 corresponds to about 340 Wm^{-2}.

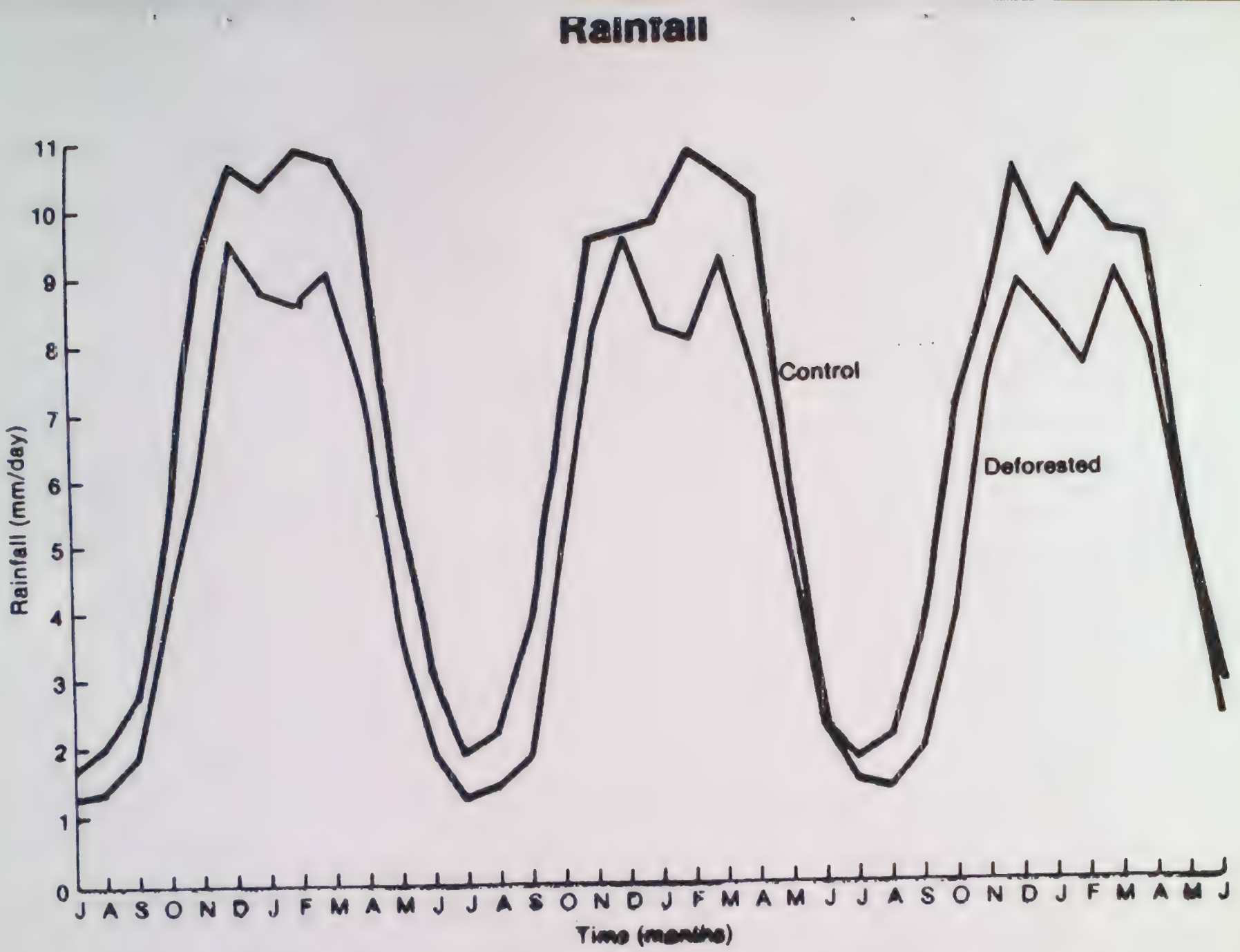


Fig 6. Monthly mean precipitation (mm/day) averaged over a large area of Amazonia for three years starting in July, in the AGCM sensitivity experiments of Lean and Warrilow (1989). The upper curve represents the control (i.e. forested) simulation, the lower curve the deforested simulation.

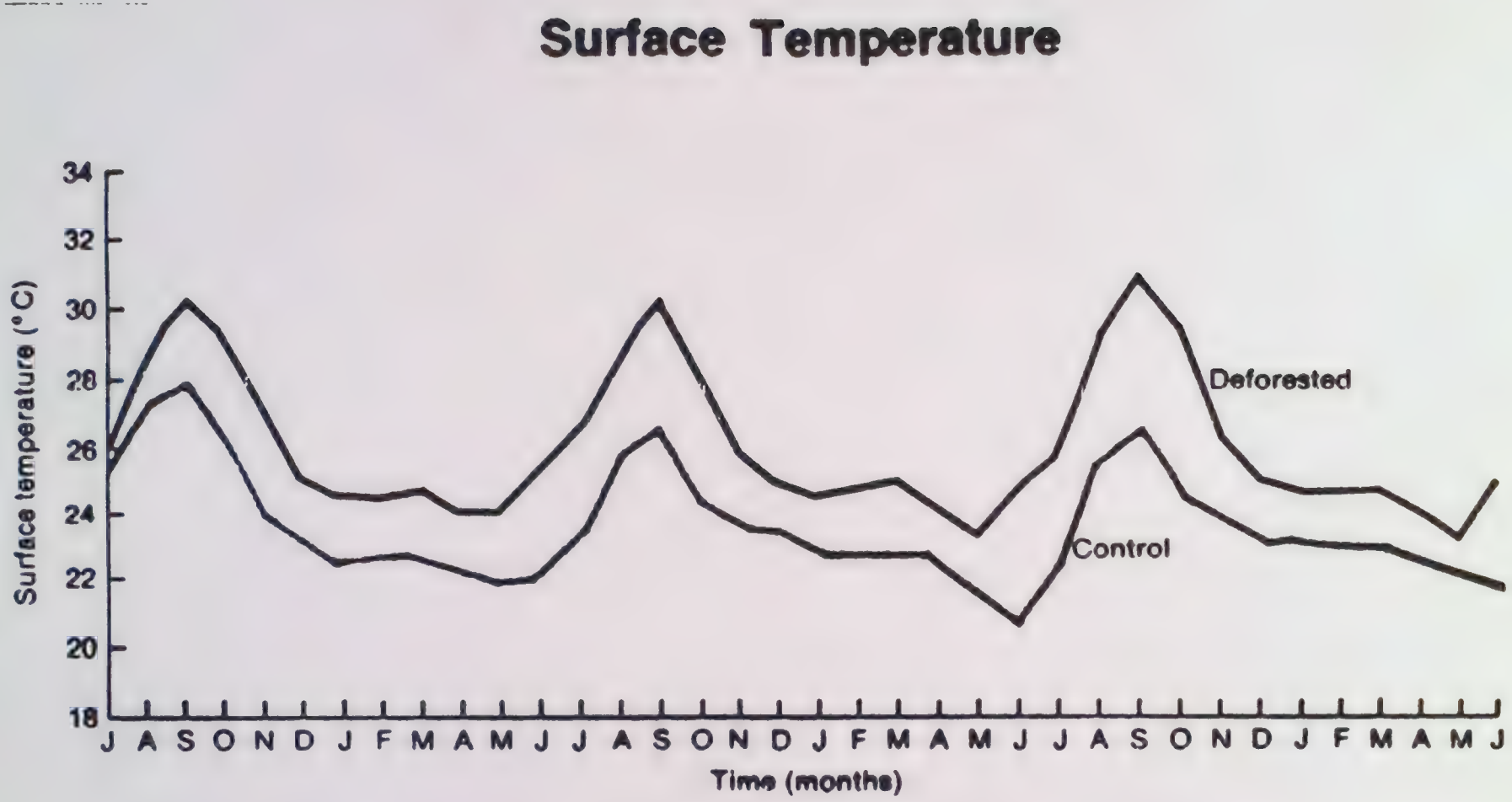
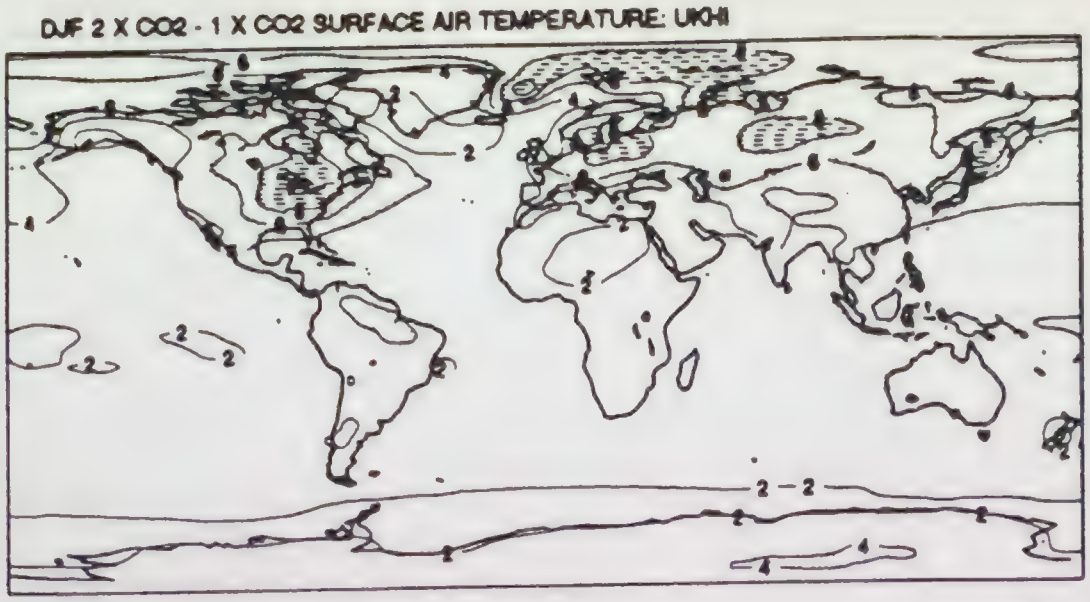


Fig 7. Monthly mean surface temperature (°C) averaged over a large area of Amazonia for three years starting in July, in the AGCM sensitivity experiments of Lean and Warrilow (1989). In this case (cf Fig 6), the lower curve represents the control (i.e. forested) simulation, the upper curve the deforested simulation.

(a)



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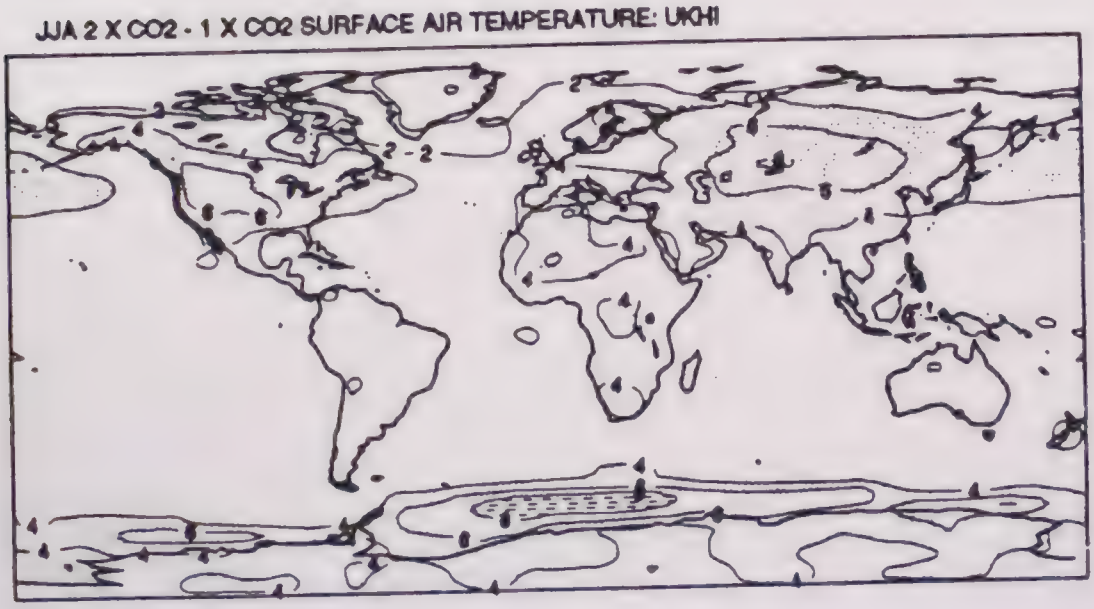
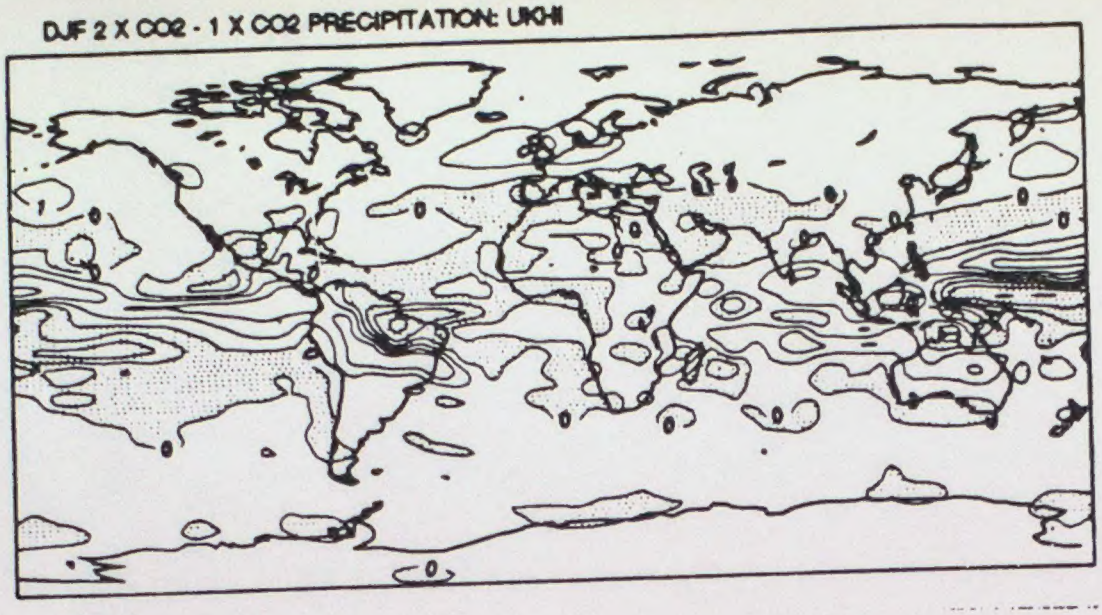


Fig 8. Change in surface air temperature (10-year means) due to doubling carbon dioxide, as simulated by a Hadley Centre high-resolution model: (a) for months of December-January-February; (b) for months of June-July-August. Contours are every 2°C, light stippling where the warming exceeds 4°C, dashed shading where the warming exceeds 8°C. (For further examples see Houghton et al (1990))

(a)



(b)

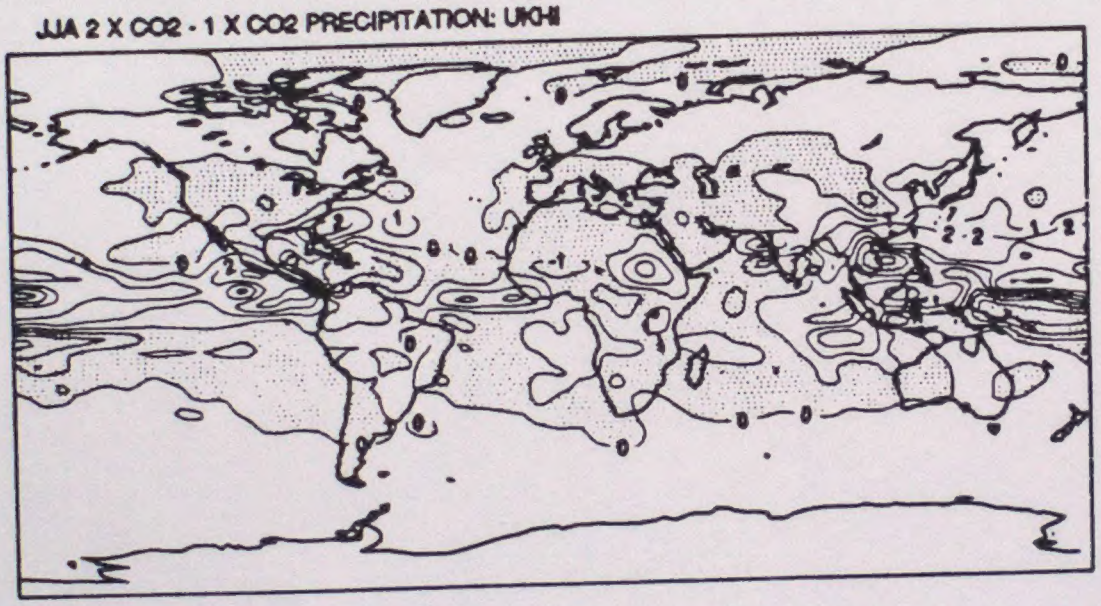
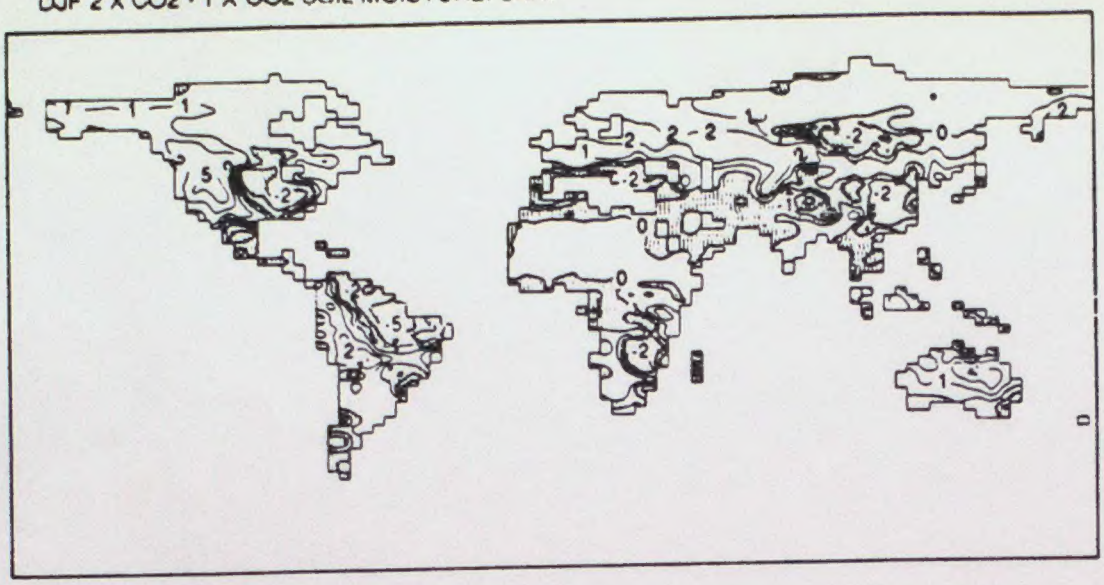


Fig 9. Change in precipitation (smoothed 10-year means) due to doubling carbon dioxide, as simulated by a Hadley Centre high-resolution model: (a) for months of December-January-February; (b) for months of June-July-August. Contours at ± 0, 1, 2, 5 mm day^{-1}, areas of decrease are stippled. (For further examples see Houghton et al (1990))

DJF 2 X CO2 - 1 X CO2 SOIL MOISTURE: UKHI

(a)



JJA 2 X CO2 - 1 X CO2 SOIL MOISTURE: UKHI

(b)

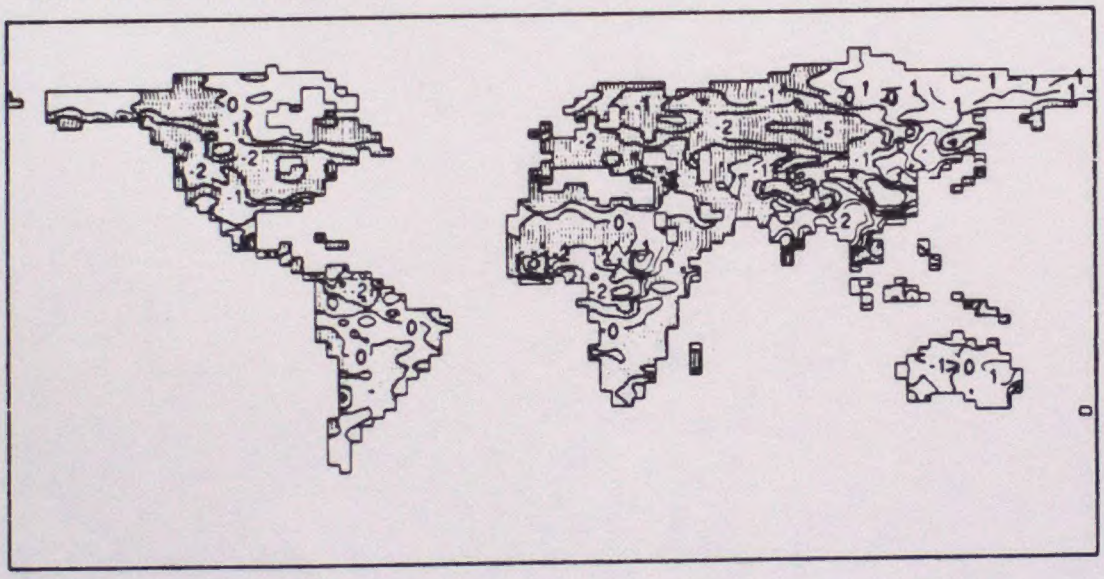


Fig 10. Change in soil moisture (smoothed 10-year means) due to doubling carbon dioxide, as simulated by a Hadley Centre high-resolution model: (a) for months of December-January-February; (b) for months of June-July-August. Contours at ± 0, 1, 2, 5 cm, areas of decrease are stippled. (For further examples see Houghton et al (1990))

COMPARISON OF OBSERVATIONS AND MODELS

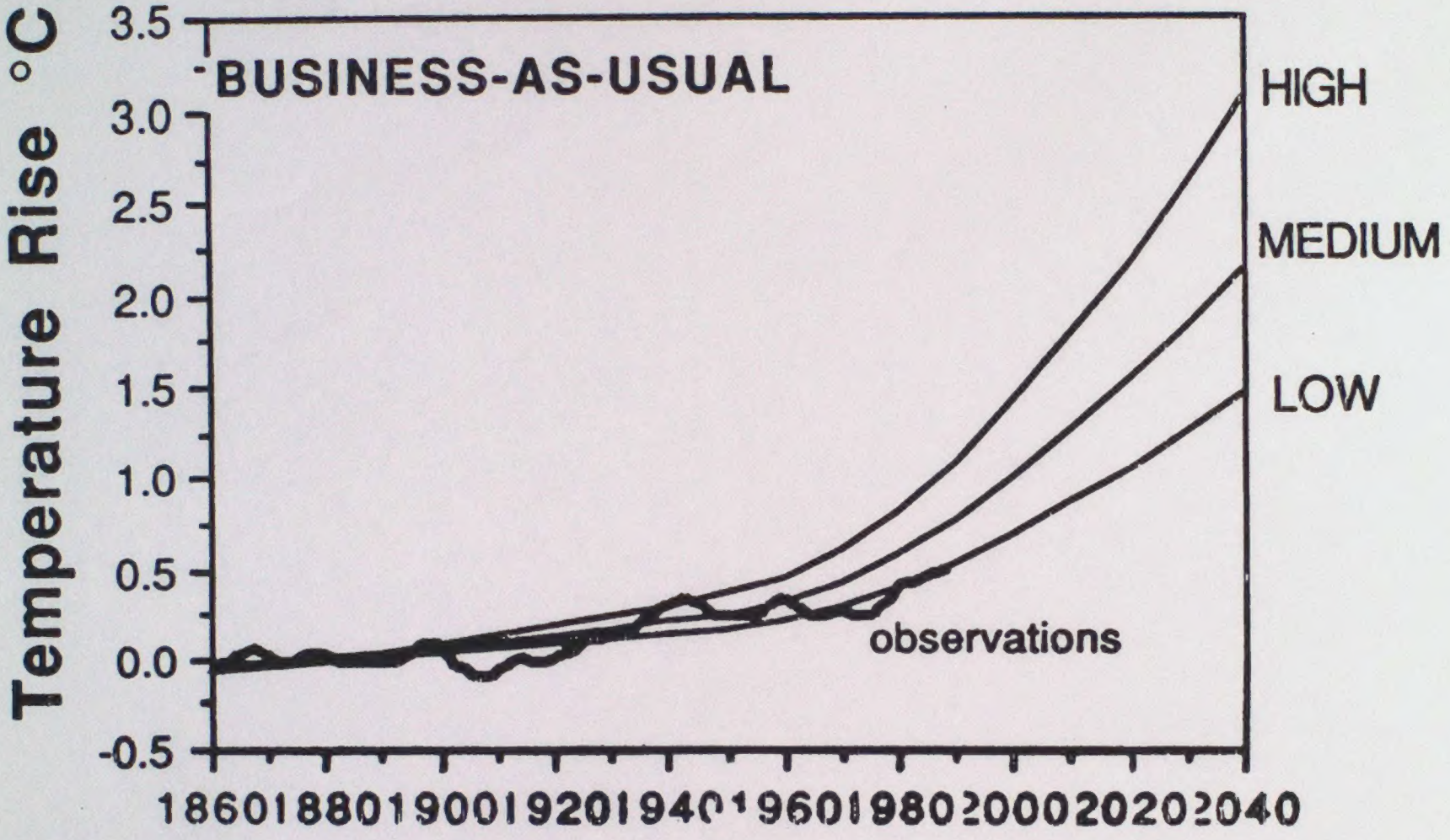


Fig 11. Simulation of the increase in global-mean temperature from 1860-1990 due to observed increases in greenhouse gases, and predictions of the rise between 1990 and 2040 resulting from the IPCC WGI Business-as-Usual emissions scenario, according to three levels of climate sensitivity (High, Medium, Low). Superimposed are the observations of global temperature changes (cf Fig 3).

CLIMATE RESEARCH TECHNICAL NOTES

CRTN 1	Oct 1990	Estimates of the sensitivity of climate to vegetation changes using the Penman-Monteith equation. P R Rowntree
CRTN 2	Oct 1990	An ocean general circulation model of the Indian Ocean for hindcasting studies. D J Carrington
CRTN 3	Oct 1990	Simulation of the tropical diurnal cycle in a climate model. D P Rowell
CRTN 4	Oct 1990	Low frequency variability of the oceans. C K Folland, A Colman, D E Parker and A Bevan
CRTN 5	Dec 1990	A comparison of 11-level General Circulation Model Simulations with observations in the East Sahel. K Maskell
CRTN 6	Dec 1990	Climate Change Prediction. J F B Mitchell and Qing-cun Zeng
CRTN 7	Jan 1991	Deforestation of Amazonia - modelling the effects of albedo change. M F Mylne and P R Rowntree
CRTN 8	Jan 1991	The role of observations in climate prediction and research. D J Carson
CRTN 9	Mar 1991	The greenhouse effect and its likely consequences for climate change. D J Carson